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LETTER TO THE EDITOR

The Influence of Residential Radon Exposure on the Estimation of Exposure–Response Trends for Lung Cancer in Underground Miners Exposed to Radon

Jay H. Lubin

Division of Cancer Epidemiology and Genetics, National Cancer Institute, 6130 Executive Boulevard, EPN/403, Rockville, Maryland 20892-7368

Radon is a potent lung carcinogen at exposure levels experienced by most underground hard-rock miners (*1*). The evidence for residential radon exposure is less certain, but current indoor studies support a small, statistically significant excess risk of lung cancer from residential radon exposure, which is consistent both with results in miners with cumulative exposures similar to exposures in long-term residents in high-radon houses (*2*) and with extrapolations from miner-based risk models (*3*). A question has arisen about the influence exposures from residential radon might have on the estimation of exposure–response trends in miners.

Suppose w is cumulative exposure to radon progeny in working level months[1] (WLM). A miner's exposure to radon progeny arises from exposures in the home, w_h, and in the mine, w_m, so that total cumulative exposure is $w = w_h + w_m$. For low exposures (<50 WLM, or $<175 \times 10^{-3}$ J h m^{-3}), a good first-order approximation of lung cancer risk, r, is given by a linear relative risk (RR) model,

$$r(w_h, w_m) = r_o(1 + \beta_h w_h + \beta_m w_m), \qquad (1)$$

where r_o is the lung cancer rate in a population not exposed to radon (i.e. exposed only at outdoor levels of radon) and includes the effects of smoking, previous lung diseases and other non-mine-related lung cancer risk factors, and where β_h and β_m are parameters for the excess RR per WLM (ERR/WLM) for exposures in the home and the mine, respectively. Under model (1), the RR of lung cancer from radon-progeny exposure (w_h, w_m) is

$$\begin{aligned} \mathrm{RR}\,(w_h, w_m) &= \frac{r\,(w_h, w_m)}{r\,(w_h = 0, w_m = 0)} \\ &= 1 + \beta_h w_h + \beta_m w_m \end{aligned} \qquad (2)$$

Assume underground exposure is unrelated to residential exposure, and let f_h be the probability density function for residential radon-progeny exposure. The marginal risk of lung cancer from mine exposures is the integral of model (1) over the indoor exposure distribution,

$$\begin{aligned} r(w_m) &= \int r_o[1 + \beta_h w_h + \beta_m w_m] f_h(w_h) dw_h \\ &= r_o(1 + \beta_h E[w_h] + \beta_m w_m) \\ &= r_o(1 + \beta_h E[w_h])(1 + \beta_{obs} w_m), \end{aligned}$$

where $E[.]$ denotes the expectation over the residential radon exposure distribution and

$$\beta_{obs} = \frac{\beta_m}{1 + \beta_h E[w_h]} \qquad (3)$$

is the marginal "observed" trend parameter (ERR/WLM) based on underground exposure to radon progeny only. The RR function for radon-progeny exposure in mines has the same linear form as for total exposure, namely,

$$\mathrm{RR}(w_m) = \frac{r(w_m)}{r(w_m = 0)} = 1 + \beta_{obs} w_m. \qquad (4)$$

Equation (3) indicates that the marginal β_{obs} is biased for the true effect in miners β_m, and that the amount of bias (β_{obs}/β_m) is a function of the mean residential exposure and the magnitude of the effect of indoor radon. This bias is not related to the level of exposure in mines. That is,

[1]One working level (WL) equals any combination of radon progeny in one liter of air which results in the ultimate emission of 130,000 MeV of energy from α particles. Working level months is a time-integrated measurement of exposure and is the product of time, in units of working months, which is taken as 170 h, and WL. In terms of SI units, 1 WLM corresponds to 3.5×10^{-3} J h m^{-3} (*4*). Residents in an average house (46 Bq m^{-3}) would experience roughly 0.2 WLM/year.

the bias associated with ignoring residential radon in high-exposure miner cohorts can be greater than or less than the bias in low-exposure cohorts.

Equation (3) defines the magnitude of the potential bias from ignoring indoor radon exposure. If indoor radon poses no health risk of lung cancer, $\beta_h = 0$, or if $E[w_h]$ is small, then there is little or no bias and the estimate of β_m from miners closely approximates the overall radon effect. However, a meta-analysis of indoor studies indicates that low exposure to radon carries some risk (*3*), and a comparison of risk from low exposures in miners and from indoor radon exposures indicates that the effect of indoor radon is not markedly different from the risk found in miners (*1*). Therefore, it is reasonable to make the assumption that the risk effects of radon in homes and mines are equal; i.e., $\beta_m = \beta_h = \beta$, and $\beta > 0$. Based on the estimate of β_{obs} from miner exposures only, the "true" ERR/WLM is

$$\beta = \frac{\beta_{obs}}{1 - \beta_{obs}E[w_h]}. \tag{5}$$

In the National Residential Radon Survey, Region 8, which included much of the Colorado Plateau mining areas, had a mean residential radon concentration of 96 Bq m^{-3} (*5*). Assuming standard occupancy and equilibrium patterns, 30 years residency at this concentration corresponds to approximately 14 WLM (*1*). A pooled analysis of underground miners restricted to exposures under 50 WLM found $\beta_{obs} = 0.0117$ (*2*). Based on Eq. (5), the "true" ERR/WLM would be 0.0140 [= 0.0117/(1 − 0.0117 × 14)]. Under these conditions, the observed ERR/WLM from the miner study may thus be 16% too low. If miners are exposed in their homes at the U.S. mean residential radon concentration of 46 Bq m^{-3}, then the observed ERR/WLM of 0.0117 would suggest a "true" ERR/WLM of 0.0127, the observed ERR/WLM being roughly 8% too low. Panel A of Fig. 1 shows the "true" ERR/WLM for a range of mean residential radon concentrations when the estimated ERR/WLM from miners is 0.0117, and panel B shows the relative bias, $(\beta - \beta_{obs})/\beta$.

The effects of ignoring indoor exposures can also affect the evaluation of modifiers of the ERR/WLM. In the miner data, the ERR/WLM declined with increasing time since exposure, attained age and exposure rate, and with decreasing exposure duration (*1*). Assuming that the effects of these modifiers were the same for mine exposures and for residential exposures, ignoring indoor exposures would reduce the magnitude of the "true" variation with age and with time since exposure, since bias is smaller when the exposure response is smaller. According to recent risk models in miners (*1*), the inverse exposure-rate effect (an increase in the effect of exposure with decreasing exposure rate) does not occur at the low exposures experienced in houses. Therefore, the increasing ERR/WLM with decreasing exposure rate in the miner data would be uniformly misspecified by the same small amount, and the relative pattern of variation would not be affected.

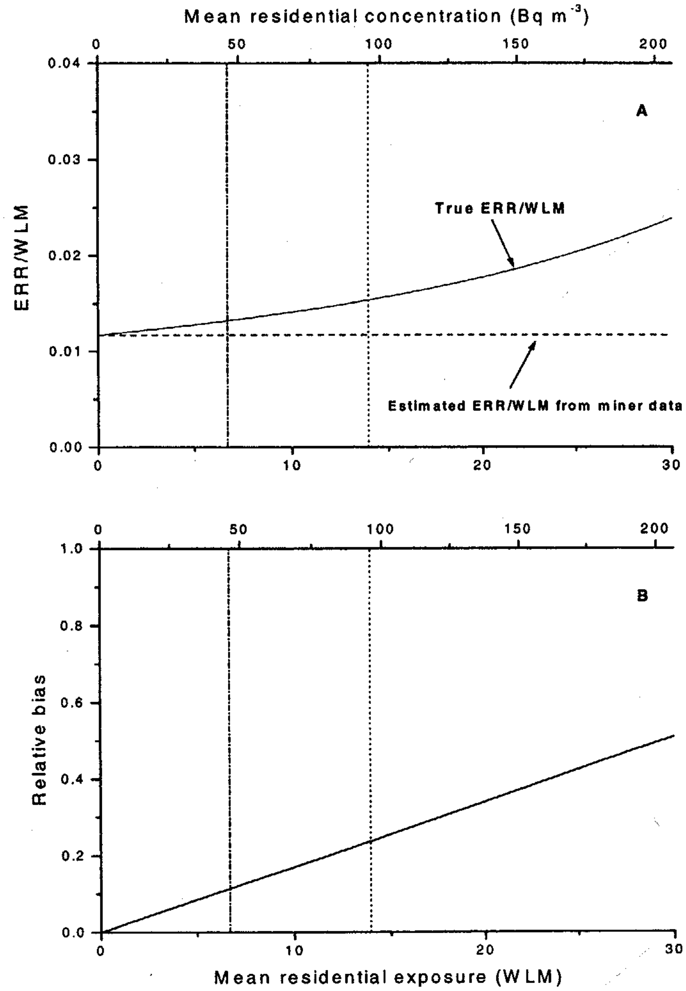

FIG. 1. The true excess relative risk per WLM (ERR/WLM) (β) and estimated ERR/WLM based only on exposures in miners (panel A), and the relative bias (panel B) by residential radon exposure. The dotted-dashed line and the dotted line denote exposure based on mean radon concentration in the U.S. and in Region 8 of the National Residential Radon Survey, respectively (*5*).

In summary, indoor radon exposure may distort the exposure–response estimate from miner studies. However, the magnitude of the bias depends on the cumulative residential, but not mine, exposure. Although miner estimates may be 10–20% too low from omitting residential exposures, this amount of deflation in the observed ERR/WLM is relatively small when compared with the twofold uncertainty inherent in the miner studies (*1*).

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